NOTES ON THE ORIGIN OF CERTAIN PALEOZOIC SEDIMENTS, ILLUSTRATED BY THE CAMBRIAN AND ORDOVICIAN ROCKS OF CENTER COUNTY, PENNSYLVANIA

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During the Cambrian period the North American continent subsided relative to sea-level. Before the close of the period epicontinental seas had transgressed the greater part of the continent now included within the borders of the United States, and, through the Upper Cambrian at least, limestone-forming conditions prevailed somewhat extensively in the central and southern Appalachian region. Whether this apparent subsidence was due to diastrophic movements or to the more or less complete base-leveling of Cambrian continental areas is not altogether certain. The type of sediments accumulated during Lower and Middle Ordovician time suggests that it was due to base-leveling rather than to diastrophism. In this central and southern Appalachian region great thicknesses of limestones accumulated between the Upper Cambrian and Trenton beds. Clastic sediments are sparsely represented and those which are present are peculiar in character. Yet land areas could not have been very far distant to the east and northeast, because in adjacent states this very time interval is represented by an unconformity and period of erosion, as for example in New Jersey.[1] The most reasonable explanation then seems to be that the adjacent land area had been reduced during the Cambrian to a peneplain. As a result, the streams and rivers did not have sufficient velocity to transport any considerable amount of clastic material into the adjacent epicontinental sea. Weathering processes, however, were at work and a thick mantle of residual rock waste was being prepared all over the peneplained land surface, only waiting for renewed stream activity to be

[1] Weller, *Geol. Surv. N.J., Report on Pal.*, III (1903), 15.

carried away. The soluble constituents, on the other hand, and particularly the lime carbonate, were being carried away in solution. This furnished the material for the thick calcareous deposits of early Ordovician time.

After this calcareous material was carried to the sea, the question arises as to how it was separated from solution and deposited as limestone. Marine animals could have done the work, but these deposits are strikingly unfossiliferous except at very widely separated horizons, and there are many peculiarities of the rock which cannot be explained upon this basis. Chemical precipitation has been suggested as a possible explanation, but this, too, is inadequate, as will be presently shown. The object of the present paper is to outline the probable course of events in Upper Cambrian and Lower Ordovician time which, it is thought by the author, will best explain the origin of these deposits and some of the peculiar physical characters which they now possess. The observations and deductions here recorded are largely based on field investigations carried on in the vicinity of Bellefonte and State College, Center County, Pa.

Rocks ranging in age from the Upper Cambrian through the Ordovician are exposed in an unsymmetrical eroded anticline which extends in a northeast-southwest direction across the Bellefonte quadrangle between the Bald Eagle Mountains on the northwest and Nittany Mountain on the southeast. This anticline pitches toward the northeast. Its northwestern limb is generally almost vertical and in some places even overturned by a few degrees. The southeastern limb, on the other hand, has very gentle dips, generally ranging from 8 to 15 degrees.

The lowest beds exposed are composed of limestone of variable character containing *Cryptozoon proliferum* in abundance and trilobites of Upper Cambrian age, the latter limited to thin fossiliferous layers. The fossiliferous layers are frequently oölitic and other oölitic layers occur. In addition to these, occasional layers of a peculiar conglomerate are found. This conglomerate is composed of broad, thin pebble-like structures ranging from half an inch or less up to three or four inches in diameter, and generally less than half an inch thick. The edges are rounded, the outline

circular, oval, or irregular, and the individual pebbles are either flat or rarely curved. They occur in the conglomerate closely packed together and in all positions relative to the bedding planes, flat, edgewise, or inclined. The frequency with which these broad, thin pebbles occur on edge has given rise in certain localities to the name "edgewise" conglomerate.[1]

Above these Cambrian limestones come a series of apparently unfossiliferous interbedded sandstones and limestones several hundred feet thick and very peculiar in character. The sandstones are composed of pure white quartz sand, extremely well rounded, and loosely cemented together by calcareous or dolomitic cement. Ordinary weathering conditions quickly remove this cement and the rock yields a thick mantle of sandy soil poorly adapted to agricultural purposes. On account of this character the region is locally known as the barrens. The interbedded limestones are of a peculiar character also. They are unfossiliferous in so far as they have been examined, and where they outcrop they stand up as hills above the adjacent sands.

These interbedded limestones were apparently formed under the same conditions as those of the underlying series, because they contain in places layers with the peculiar flat pebble-like structures and scattered oölite grains. Certain beds have peculiar wavy structures which give to the rock an appearance somewhat like the fossil *Cryptozoon*, but it seems to be wholly due to a mechanical distortion by lateral compression of the thin beds making up the rock. Generally the contact between these interbedded limestones and the overlying sands is very obscure because of the rapid disintegration of the sandstone. In one case the transition was observed. In it the upper layer of limestone, about a foot thick, contained numerous flat pebbles and a few oölites scattered through it. This was succeeded by about two feet of very thin-bedded fine sandstone approaching shale in appearance, with numerous sun cracks or mud cracks distinctly preserved in certain layers. Then came the sand composed of extremely well-rounded sand grains.

The next overlying formation is a limestone, sometimes sandy and sometimes shaly, carrying a rather scant fauna of Lower

[1] Stose, *Folio 170, U.S. Geol. Surv.*

Ordovician age. In addition to the sandy and shaly layers and the normal limestones, several beds of oölitic rock are also present. In these the oölites are comparatively large in size and at many horizons have been replaced by silica giving rise to the siliceous oölites of this region which are represented in almost every geological collection.[1]

Beds of the peculiar thin pebble conglomerate already described under the Cambrian also occur here and, in fact, make up a half or more of the first few hundred feet of the Beekmantown limestone. These conglomerate layers vary somewhat in character. In every case examined the pebbles consist of extremely fine-grained calcareous material and, except on weathered surfaces, the conglomerate character cannot as a rule be easily recognized. On a fractured surface the interior of the pebble-like structure is almost identical in appearance with the surrounding matrix. On a weathered surface these structures show a different, generally lighter, color and are easily recognized. They are exceedingly variable in size and shape. In some beds they are round or oval and when viewed in the hand specimen have the characteristic appearance of water-worn pebbles. They are generally thinner in one direction and in thin section often show a peculiar concentric banding following parallel to the broader sides. Occasionally a pebble can be found with a fossil shell inclosed. In the majority of the beds the pebbles are broad and flat, ranging up to three or four inches in diameter and generally less than half an inch thick. They are found in all positions in the beds, some lying flat parallel to the bedding planes and some even standing on edge. Under certain conditions these broad flat pebbles have been replaced either in part or completely by silica in the form of chert, while the surrounding matrix remains calcareous. When only partially replaced, the replacing silica forms shell-like layers around the exterior of the structure, while the central part remains calcareous and unchanged.

[1] For published descriptions of these see V. Ziegler, *Am. Jour. Sci.*, 4th ser., XXXIV (1912), 113–27; E. S. Moore, *Jour. Geol.*, XX (1912), 259–69; G. R. Wieland, *Am. Jour. Sci.*, IV (1897), 262–64; J. S. Diller, *Bull. U.S.G.S. No. 150* (1898), pp. 95–97; E. O. Hovey, *Bull. Geol. Soc. Am.*, V (1893) 627–29; E. H. Barbour and J. Torrey, *Am. Jour. Sci.*, XL (1890), 246–49.

This series of strata, ranging from the Upper Cambrian well into the Ordovician, represents a peculiar combination of oölites, rounded sand grains, and unusual conglomerate-like beds which requires more than ordinary conditions of sedimentation to explain. After detailed study both in the field and in the laboratory, it seems to the author that these structures can be best explained individually, and as a combination, by the following series of events.

Toward the close of Cambrian time an epicontinental sea covered this region. The adjacent land area was in a state of peneplanation, thus furnishing very little clastic sediment but probably still contributing considerable quantities of calcium carbonate in solution. This lime carbonate was removed from the sea water and deposited as limestone by the activities of marine organisms. Marine animals, trilobites, brachiopods, and probably many other less highly organized types like the sponges aided in this work, but the greater part of the separation and secretion of the lime was brought about by marine algae which gave rise to the oölites and peculiar pebble-like structures. Then the region was somewhat elevated and sand-dune conditions prevailed. These marine limestones were covered over by a thick blanket of wind-blown sand. This material was worked over by the wind so long and so thoroughly that even the minute grains were rounded into almost perfect spheres. This sand resembles, but is even more rounded than, the beach and dune sand along the Florida coast today, which has gradually been carried southward by the wind and water and rounded during its journey. The region was not very far above sea-level and at least twice during the accumulation of these sands it was submerged and thin beds of limestone similar to those of the preceding period were formed. After this complete series of sandstones and limestones had accumulated, the whole region was finally submerged and the continuous marine sedimentation of early Beekmantown time was inaugurated. However, marine algae were still the important agents in producing the limestone, because, as already noted, oölitic limestone and siliceous oölite occur at numerous horizons and a large percentage of the lower beds is composed of the peculiar pebble-like conglomerate secreted by the algae.

These structures are of sufficient importance to require further explanation and it will be advisable to consider them one at a time, taking the conglomerates first, the oölites next, and the interbedded sands last.

ORIGIN OF THE CONGLOMERATE-LIKE STRUCTURES

Conglomerates from widely separated regions, similar to those here mentioned, have previously been described by other authors.

In 1906 a similar if not identical conglomerate was described by Seeley from Division D of the Beekmantown of the Champlain Valley, under the name of the Wing conglomerate.[1] He quotes Wing's original description of this conglomerate as follows: "A conglomerate made from flat and rounded pebbles from the quartzite below, the flat ones one or two inches across, the rounded ones from coarse shot to large bullets, the paste a limestone." After questioning as to the origin of these pebbles, Seeley remarks that the associated deposits seem to have been laid down in quiet waters and that the flattened pebbles, as described by Wing, stand on edge and at all angles. He was unable to imagine how in either swift or slow water these pebbles could be laid down as they are if they were of clastic origin. As a result of his studies he concluded that they were organic and he described the pebbles as *Wingia*, a new genus of Beekmantown sponges.

In 1909 Stose described conglomerates identical with those now under discussion from the same geological horizons near the southern boundary of Pennsylvania.[2] He offers the following explanation of their origin:

> At the beginning of the Conococheague an uplift occurred that raised a part of the sea bottom into land. The freshly deposited sediment was broken up and its fragments formed conglomerates, which also contain numerous rounded quartz grains. Other thin layers of limestone were broken up by the waves into "shingle" or flat fragments that were shuffled about on the beaches and formed "edgewise" conglomerates.

A very careful study of these conglomerates, both in the laboratory and in the field, with attention directed not only to the larger

[1] H. M. Seely, *Report of the Vt. State Geol.* (1906), pp. 174–78.

[2] G. W. Stose, *op. cit.*

structures of the conglomerate bed, but also to the minute microscopic structure of the individual pebbles, has brought out some interesting features not hitherto noted in the descriptions. It has already been stated that these peculiar conglomerate pebbles have a wide range in size and shape and that they occur associated with oölite grains. Although the pebbles are broad and flat, the edges and corners are always rounded. Thin sections cut from these pebbles show a peculiar banding in the broad flat types and a concentric structure in the smaller rounded specimens (Figs. 1, 2). The pebbles are frequently partially or completely replaced by silica in the form of chert. In such cases the matrix weathers away and leaves the replaced pebbles like chert concretions. If the replacement is incomplete and a joint plane passes through the pebble, the central unreplaced part also weathers out, leaving the chert nodule hollow.

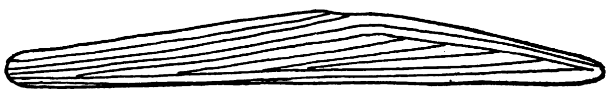

FIG. 1.—Cross-section of a broad flat pebble as it appears on a weathered surface. The weathering brings out the arrangement of the laminae. Natural size.

As an outcome of these studies it has been concluded that these structures are organic, resulting from the activities of calcareous algae. This conclusion differs from Seeley's in assigning the origin to algae instead of sponges. Seeley was undoubtedly led to assign these structures to the sponges because of the frequency with which he found them containing silica. He describes *Wingia* as "a calcareous fossil sponge, with or without siliceous spicules . . . . the essential structure a collection of pillae or tufted balls, these mostly 0.25 mm. in diameter, massed without definite arrangement or rarely more loosely distributed through the containing calcite." These siliceous structures are no doubt replacements of the original calcite similar to those found both in the pebbles and in the oölites of the Pennsylvania region.

The importance of the lime-secreting algae seems to have been generally overlooked in explaining the origin of early Paleozoic limestones. Even in the building-up of modern calcareous deposits

these forms have been given scant credit. A recent contribution on this subject[1] by Howe has indicated how important these organisms really are in building up the reefs of today. The lack of recognition of these forms as important reef-builders is no doubt due to two facts. In the first place, the skeletons of these calcareous algae either have been assigned to true corals and therefore credited to the animal kingdom, or, on the other hand, they have perhaps been considered by some, direct chemical precipitates rather than organic structures. In the second place, these calcareous algal skeletons lose their organic character with great rapidity. Walther has shown by his studies on the *Lithothamnion* bank in the Bay of Naples that by the action of the percolating water the *Lithothamnion* structure is gradually obliterated and the calcareous mass becomes a structureless limestone. In studying Nullipore chalk from the Tertiary and from the Lias, Walther found that in many parts there occurred well-preserved specimens but in other parts a gradual obliteration is observed of all plant structures until the rock becomes entirely structureless. If this be true for a form like *Lithothamnion* which is known to secrete a calcareous skeleton whose mineral composition is calcite, it is not surprising that all trace of organic structure is lost in other types which, like *Halimeda*, secrete their skeleton in the mineral form of aragonite.[2]

FIG. 2.—Thin section of small pebbles showing concentric structure. Enlarged.

It is freely admitted that in these pebble-like structures from the Cambrian and Ordovician limestones no organic structure has been found sufficiently well preserved to prove conclusively that they are of algal origin, but their similarity to such structures now forming is very suggestive. In this connection it is worth

[1] M. A. Howe, "The Building of 'Coral' Reefs," *Science*, May 31, 1912.

[2] W. Meigan, *Centralblatt für Min., Geol., und Pal.* (1901), pp. 577, 578.

while to compare the following quotations concerning modern occurrences.

There is also a small vegetable group, that furnishes a considerable quota toward the composition of the characteristic coral-rock. It is that of the peculiar seaweeds or lower algae known as Corallines or Nullipores. They are distinguished by the incrustment of their tissues with carbonate of lime, to such density that their vegetable nature is completely disguised; and, excepting for the absence of the characteristic pores, they might in many instances be mistaken for the coralla of the hydroid coral Millepora. . . . . In the deeper rock pools, and on the sea bottom generally, in the neighborhood of the reefs, another generic form, Halimeda, belonging to the same nullipore tribe, is locally abundant. This type forms erect, branching tufts, often several inches in length, of which the branchlets are composed of flattened, irregularly polygonal, or more or less fan-shaped, calcareous disks, strung together, as it were, in a moniliform or chainlike order. While growing, this nullipore is a brilliant grass-green, but it bleaches, when dead, to a pure white. The bleached discoidal segments of its disintegrated fronds often occur in great abundance among the mixed calcareous components of reef-rocks and coral sand.[1]

In describing the reefs of the Bahamas Agassiz says:

Nullipores are most abundant on the summit of the reef, growing upon the smaller fragments of broken corals, which they also often cement together, when they are forced inward into the deeper part of the lagoon, where the cemented masses frequently form heads of considerable size. Longitudinal and cross-sections of the lagoon show that its bottom is uniformly covered with coarse sand and broken shell material, or fine sand, according to the distance from the action of the breakers. Upon this looser material algae and corallines thrive and grow abundantly, generally in large patches.[2]

Immense masses of nullipores and corallines grow on the shallowest flats, on the tops of the branches of madrepores which have died from exposure to the air, either because they have grown up to the surface and so have become exposed by extreme low tides, or because strong winds have blown the water from the flats.[3]

Not only are the Nullipores very abundant in many of the modern coral reefs but they also seem to be able to grow with great rapidity and they can live under all conditions—in deep water beyond the range of corals; in shallow water where they are

[1] W. Saville Kent, *The Great Barrier Reef of Australia*, (1893), pp. 140–41.

[2] Agassiz, *Bahamas*, p. 104; *Bull. Mus. Comp. Zoöl.*, XXIV (1894).

[3] Agassiz, *Three Cruises of the "Blake,"* I, 82.

uncovered for a part of the time each day; in the tropics where the water is warm; and in the cold waters north of the polar circles.

The remarks of Saville Kent concerning the disklike fragments of *Halimeda* mingled with the sands of the great barrier reef are very suggestive of the disklike structures here described. The range in size of these disks is very much greater than that found in the modern *Halimeda* but it is quite possible that a giant *Halimeda*-like form existed in these early paleozoic seas and gave rise to the structures here described.

One feature of the conglomerate beds yet awaits explanation; namely, the peculiar position frequently occupied by the broad flat pebbles, either on edge or at any angle to the bedding planes. Several explanations of this feature have previously been offered. As noted above, Seeley believed these pebbles were formed by sponges growing in place. Stose thought that they were formed by thin limestone layers breaking into small flat plates or shingle and tossed about on a tide-swept flat. When the tide came in, these flat fragments were washed together in all positions and held by a soft paste which surrounded them. This explanation seemed impossible to the author for two reasons: first, it would not account for the wide variations in the thickness of the conglomerate beds, which varies from a few inches to several feet, each bed being a definite unit and separated from those adjacent by parallel bedding planes; and secondly, it seemed impossible to conceive of the physical conditions which could roll these flat pebbles around until their edges and corners were rounded and then leave them indiscriminately mixed with a soft matrix, some lying flat, some on edge, and others at all possible angles between these two.

The true explanation of the origin of these conglomerates became apparent when a locality was visited along the railroad cut of the Lewisburg and Tyrone division, Pennsylvania R. R., beside the Logan Branch of Spring Creek, at a point opposite the Nittany Furnace in Bellefonte. At this point several hundred feet of limestone beds are exposed in a steeply dipping series along the railroad cut. The excavation in this cut has exposed the beds in vertical section and the arrangement of the broad flat pebbles becomes at once apparent. This arrangement is clearly shown in

the accompanying diagram and photograph (Figs. 3, 4). Here the pebbles are seen to be arranged in unsymmetrical wavelike or ripple-like structures which traverse the limestone. In this cut the beds are exposed at right angles to these wavelike structures and the arrangement is brought out with almost diagrammatic clearness. Each series of waves is confined to its own particular stratum of the limestone. When the wavelike layer of flattened pebbles arches up to form an unsymmetrical anticline the fine-

FIG. 3.—Photograph of a thin conglomerate layer in place, near Bellefonte, Pa.

grained material fills the space beneath the anticline down to the prominent bedding plane below. The space between the upper surface of this pebble layer and the next overlying prominent bedding plane is also filled by fine-grained material, which thickens over the synclines and thins out over the anticlines.

The explanation offered for these structures is this: The sediments composed of fine-grained calcareous mud resulting from the grinding-up of calcareous organic structures by wave action and broad flat pebble-like bodies which were the skeletons of cal-

careous algae accumulated on the gently sloping bottom of the sea. When in their original position these pebbles were all flat and parallel to the bottom; in other words they lay parallel to the bedding planes. At periodic intervals these beds of calcareous mud and intermingled pebbles slumped or slid along the bottom under the influence of gravity. At the time of the slump or slide the matrix around the pebbles consisted of incoherent lime mud or paste. As it moved it developed unsymmetrical waves or ripples

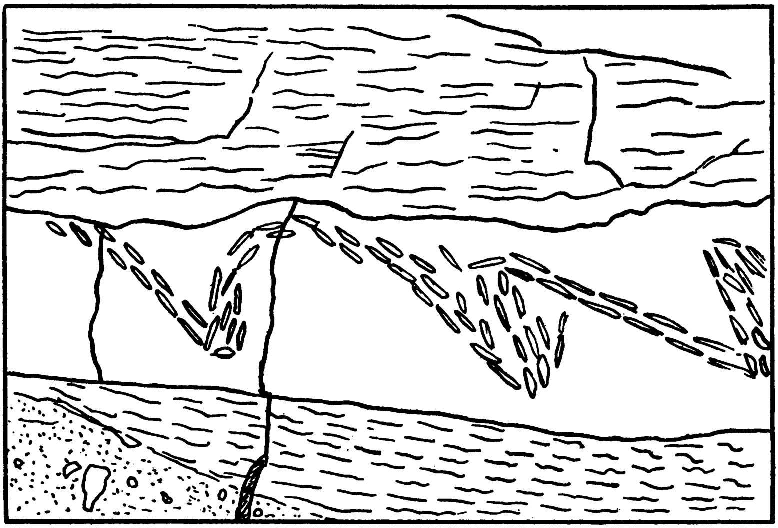

FIG. 4.—Diagram illustrating the arrangement of the pebbles shown in Fig. 3. The conglomerate bed is 6 inches thick and the distance from crest to crest of the wavelike structures is 9½ inches.

in its mass, just as a thin sheet of water develops ripples as it flows down a smooth, gently sloping surface. The whole layer of sediment when it finally came to rest—and the whole distance moved may have been only a few inches or possibly a few feet—settled into a uniform layer once more, but the inclosed pebble-like structures had been moved from their original horizontal position, and occurred at all angles with the original bedding planes. In these new positions, surrounded by the matrix of lime mud, they were in perfect equilibrium and there they remained until the lime mud became transformed into limestone. And there we find them today when

properly exposed in cross-section, still indicating the wavelike flowing motion which brought them into their present position.[1]

ORIGIN OF THE OÖLITES

Oölites are widely distributed in the rocks of this country and Europe and are found at many horizons from the Cambrian (or even pre-Cambrian)[2] to the present. They are known to be accumulating today at numerous places among which may be mentioned certain coral reefs in the open sea, as, for example, those around Bermuda and the Bahamas, in Salt Lake, Utah, and in certain petrifying springs like those at Carlsbad.

The oölites of the central Pennsylvania region are somewhat variable according to the horizon at which they occur. In the Upper Cambrian limestones they are apparently all calcareous, either spherical or oval in shape, composed of concentric layers of material generally showing a radial fibrous structure. Between crossed nicols some of the spherules show a characteristic dark cross, while others have been almost completely transformed into a single calcite crystal with twin lamellae distinctly developed. No nuclei of foreign material were observed; the fibrous concentric structure continued to the center, or the calcite crystal occupied this central position with only the marginal fibrous part remaining. Associated with these spherical forms were numerous oval and rodlike structures having an internal make-up similar to that of the oölites. The spherical oölites range in diameter from 0.28 mm. to 0.73 mm. The oval and rodlike grains also show considerable variation in size, as these measurements will show: large oval oölite grain, long diameter 1.02 mm., short diameter 0.57 mm.; small oval grain, long diameter 0.86 mm., short diameter 0.28 mm.; long rodlike grain, long diameter 2.04 mm., short diameter 0.28 mm.

The siliceous oölites and the associated calcareous oölites from the Ordovician beds are sometimes larger in size. Several measure-

[1] I am indebted to Professor A. W. Grabau and Dr. F. F. Hahn of Columbia University, who first brought this explanation to my attention. Dr. Hahn has made a special study of such motion in stratified deposits. He informs me that in recent sediments in the Zuider Zee such a slumping or flowing of the sediments has been observed where the slope of the bottom did not exceed four degrees.

[2] See Geikie, *Text-Book of Geology*, p. 192, footnote.

ments of the spherical grains from that locality where they seem to be largest show that the range for the diameters is between 1.00 mm. and 1.33 mm. Many of the grains are partially or completely replaced by silica and a rounded sand grain frequently forms the nucleus around which these oölites have formed. In the course of this replacement the central nuclear sand grain is sometimes secondarily enlarged, showing a zonal structure in optical

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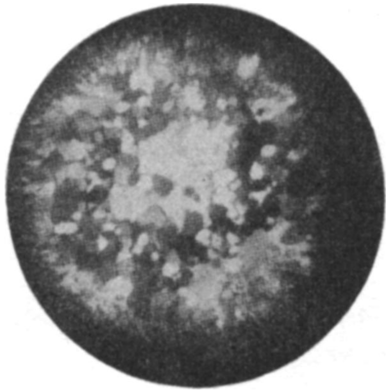

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FIG. 5.—Photomicrograph of siliceous oölite; ×22. The oölite on the left shows an oval sand grain as a nucleus, surrounded by cryptocrystalline quartz, with a narrow zone of minute quartz crystals radially arranged around the outer margin. The upper oölite shows the central nuclear quartz grain secondarily enlarged into a quartz crystal with part of the crystal faces developed. The lower oölite shows the central space occupied by an aggregate of minute quartz crystals. Nicols crossed.

FIG. 6.—The interior of the oölite of Fig. 5, ×130, showing the crystal outlines of the minute quartz grains which compose it. Nicols crossed.

continuity with the original grain and sometimes with more or less completely developed crystal faces. The outer zones of the spherules are generally replaced by cryptocrystalline quartz or chert. When no nucleus is present this chert may extend to the center or the center may be occupied by numerous distinctly crystallized quartz grains. Some of these show crystal faces as if the minute central cavity had been filled like a tiny geode. Another very interesting feature is the secondary enlargement of the spherules by one or more zones of crystalline quartz deposited in minute radial crystals arranged in zones around the original granule, with the long axes of the crystals arranged normal to the outer surface of the sphere (Figs. 5, 6).

Two theories have been advanced to explain the origin of these oölitic grains. Some hold that they are chemical precipitates and that the concentric oölitic structure is produced by successive layers of calcareous or siliceous deposit laid down on minute fragments of shells, sand grains, etc., in highly calcareous or siliceous waters. An alternative hypothesis, and one which seems more probable, is that cellular plants (algae) have extracted lime carbonate from the water, and have built this up into oölite grains with a concentric and fibrous radiated structure. All other types of oölites are then derived from these original calcareous grains by replacement. Such lowly organized plants can live even in hot waters, and oölite grains are now forming in springs like those at Carlsbad, due to the activity of algae.[1] In 1891 Rothpletz visited Salt Lake and made a detailed study of the oölitic sand now forming along the shore.[2] He found that oölites dredged up from the bottom, which had not been worked over by the waves, were covered with a deep bluish-green mass of algae among which he recognized *Gloeocapsa* and *Gloeotheca*. As a result of his studies he concludes:

> The oölites of the Great Salt Lake are, therefore, indubitably the product of lime-secreting fission-algae, and their formation is proceeding day by day. . . . . According to the present stage of my researches, I am inclined to believe that at least the majority of the marine calcareous oölites with regular zonal and radial structure are of plant origin, the product of microscopically small algae of very low rank, capable of secreting lime.

Another interesting suggestion, particularly when considered in connection with the foregoing discussion of the algal origin of the conglomerate-like beds, is that made by Seeley in which he called attention to the close resemblance of the internodal grains of Nullipores to grains of oölite as furnishing a further explanation of oölitic texture. These grains show a concentric structure as well as a radiated tubular structure, which would favor the recrystallization such as commonly occurs.[3]

In 1903 G. Linck published the results of his investigations

[1] Geikie, *Text-Book of Geology*, I, 191.

[2] *Botanisches Centralblatt*, Nr. 35 (1892). Translated in *Am. Geol.*, X (1892), 279–82.

[3] H. G. Seeley, *Brit. Assoc. Adv. Sci., Bath* (1888), *Proc.*, pp. 674–75.

concerning the origin of oölites.[1] He proved that in every recent occurrence of oölite of which he was able to obtain samples, the oölite grains consist of the mineral aragonite, while in the older or fossil types they consist of calcite. He concludes that all oölites were originally formed as aragonite and later changed to the more stable mineral form calcite. But aragonite cannot form under any ordinary marine- or fresh-water conditions due to simple concentration of the solution of calcium bicarbonate. There are then two possible conditions under which the aragonite oölites might have accumulated. They might be the products of organic activity, for it is known that both animals and plants have the power to abstract calcium carbonate from the water and build it up into their skeletons in the form of aragonite. The skeletons of many of the coralline algae, for example, are formed in this way. The oölite grains might also be produced by direct chemical precipitation due to some special precipitating agent. By experimental research Linck found that, under ordinary conditions of temperature, the calcium carbonate would be precipitated from the calcium sulphate of sea water by the addition of sodium carbonate or ammonium carbonate. When so precipitated it assumed the mineral form aragonite. As a result of his investigations he concluded that although the solution of calcium carbonate (bicarbonate) in sea water was always below the saturation point, and therefore direct precipitation due to concentration could not take place, yet sodium carbonate or ammonium carbonate might arise, due to the decay of plant or animal tissues, and that these reagents would precipitate the calcium carbonate from the ordinary sea water, under either cold or warm climates, in the form of aragonite, and that in this way the oölite grains were formed.

This theory does not eliminate the organic factor in the production of oölite grains, but makes the organisms indirect agents which produce by their decay sodium or ammonium carbonate, the precipitating reagents, instead of directly building the oölite grains by their organic activity.

It would therefore seem that under either the organic or inorganic theory of origin we must postulate the presence of organisms

[1] *Neues Jahrbuch für Min., Geol., und Pal.*, Beilage-Band XVI (1903), 495–513.

to cause the formation of oölites. Now, since many of the oölite layers show no evidence of the presence of animal fossils, it would seem to be reasonable to assume that the organic agents were marine algae, either of the coralline type, somewhat similar to those which abound wherever oölites are known to be forming in the open sea today, or minute algae similar to those which are known to be active in the formation of oölites in Salt Lake or the hot springs of Carlsbad.[1]

In spite of recent publications to the contrary,[2] the author has in his possession material which will, he is convinced, when thoroughly worked up, prove that every occurrence of siliceous oölite in the Ordovician rocks of Pennsylvania is due to the direct replacement of an original calcareous oölite by silica. These siliceous oölites occur at many horizons and in many localities. They sometimes occupy widely extended layers, and sometimes occur as nodules in layers where the surrounding oölites are either calcareous or changed to dolomite. In every case when found in place, their field association and microscopic character is such that they could not have formed as direct chemical precipitates.

ORIGIN OF THE BARRENS SANDSTONE

As already noted, these sandstones are composed of fine, extremely well-rounded sand grains cemented by a calcareous or dolomitic cement which easily weathers out and gives rise to a thick mantle of residual sand. The sand grains seem to be uniformly rounded regardless of size. A thin section cut from the basal member of this series showed grains ranging from 0.17 mm. to 0.73 mm. in diameter (see Fig. 7). A sample of the residual sand from the middle of the series gave measurements from 0.13 mm. to 0.71 mm., and a similar sample from the upper beds showed diameters from 0.26 mm. to 0.86 mm.

As is well known, such fine sands could not have been rounded to such a degree in water. It seems, therefore, that the origin of these sands and sandstones must be assigned to the work of the

[1] The author has under way a further investigation of the origin of oölites, but the results are not yet available for publication.

[2] Ziegler, *Am. Jour. Sci.*, 4th ser., XXXIV (1912), 113–27.

wind. These sands are almost always pure white in color, differing from typical desert sands, which are generally some shade of red or brown, so that in all probability desert conditions did not prevail here. It was more likely a stretch of sand-dune country that lay along the low, flat Upper Cambrian shore. At that early day those types of plant life which check the development of sand dunes along our shores today did not exist and perhaps there was no other type of plant to take their place. As a result the wind had unhindered opportunity to get at and work over this sand. The climate need not have been very dry, because, as Shaler has shown, rain does not have an important retarding effect upon wind-blown sand.[1] Even heavy and long-continued rains falling upon dune sand rarely wet it for more than an inch below the surface. In a few hours after the rain is over, this thin film of water is evaporated from the surface and the wind is free again to move about the sand. The cross-bedding shown in the few localities where this sandstone outcrops is altogether consistent with this sand-dune theory of origin. When again the region became submerged, a little of the finer sand was carried out and dropped in the water. These grains then frequently served as the minute nuclei around which calcareous oölites formed, which were in many cases later replaced by silica and gave rise to the extensively developed siliceous oölites of the overlying beds.

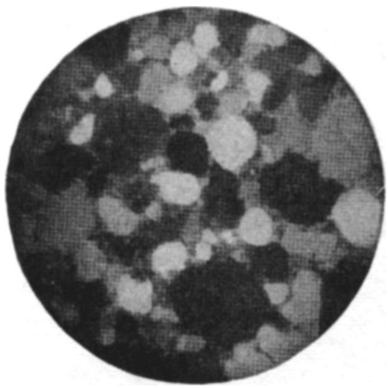

FIG. 7.—Photomicrograph of the Barrens sandstone. ×22. Nicols crossed.

This sand-dune theory of the origin of the sandstone beds does not require great changes in the conditions of sedimentation from the Upper Cambrian to the Lower Ordovician of this region, nor does it require long periods of time to produce the well-rounded character of the sand. Mackie has shown that sand carried by the wind for a very few miles will be more thoroughly rounded than

[1] N. S. Shaler, *Bull. Geol. Soc. Am.*, V, 207–12.

similar sands carried for many miles by water or subjected to long-continued churning by the waves.[1]

A slight elevation of the region, perhaps only a few score feet, would allow the sand dunes to migrate out over the Upper Cambrian limestones. No elevation of the adjacent land area is necessary to account for the transportation of the sand, because the wind is well able to transport sand grains of such small size for long distances if not interfered with by vegetation. Very slight depressions would account for the thin interbedded limestones, and a general though gentle submergence of the whole area would inaugurate Beekmantown time.

[1] Mackie, "On the Laws That Govern the Rounding of Particles of Sand," *Trans. Edinburgh Geol. Soc.*, VII, 298–311; see also pp. 148–72 (1897).